(54) Title: OPTIMIZED SOLDER JOINTS FOR SURFACE MOUNT CHIPS
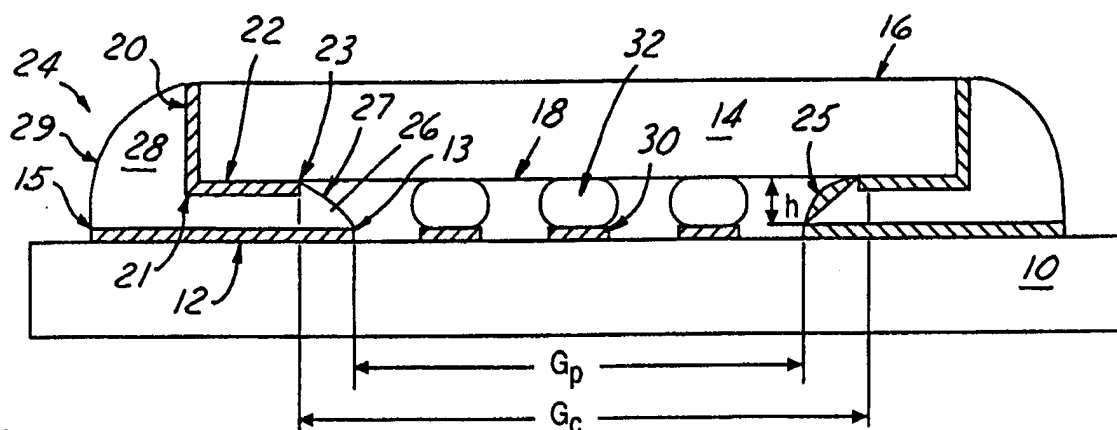
(57) Abstract

There is disclosed herein a surface mount printed circuit board having a substrate (10), at least one surface mount device (14), at least two mounting pads (12) per device (14), solder joints (24) connecting the terminations (22) of the device (14) to their respective mounting pads (12), at least one rectangular lifter pad (30) on the substrate (10) amid the mounting pads (12), and a solder mass (32) on each lifter pad (30) in contact with the bottom surface (18) of the device (14). The inner and outer extensions (l_i and l_o) of the mounting pads (12), the size, number, and shape of the lifter pads, and the amounts of solder deposited on the mounting and lifter pads (30) are designed such that the solder joint (24) has preferably convex outer fillets (28), the device (14) is maintained at a predetermined height (h_o) above the mounting pads (12), the inner fillet angle (α) is maintained above a predetermined minimum angle to increase solder joint crack initiation time, and the overall solder joint crack propagation length is increased. An alternative embodiment also includes plugged vias (34) under the lifter pads (30) and/or mounting pads (12), with gas pockets (40) trapped between the solder masses (32) /solder joints (24) and the plugged vias (34). This trapped gas pocket (40) provides additional buoyant force upon the SMD (14) during reflow.

OPTIMIZED SOLDER JOINTS FOR SURFACE MOUNT CHIPS

The present invention relates generally to printed
circuit boards. More particularly, the present invention
5   relates to printed circuit boards having surface mount
devices with improved solder joints.

In the field of surface mount printed circuit boards
(PCBs), an important indicator of solder joint durability is
10   the time required for a solder joint of a surface mount
device (SMD) to fail under given conditions of cyclic
temperature variation. FIG. 1A shows a typical surface
mount PCB having an SMD 14 joined to a mounting pad 12 on a
PCB substrate 10 by a conventional solder joint 24. The
15   solder joint 24 has an inner fillet 26 adjacent the device's
bottom surface 18 and the mounting pad 12, and an outer
fillet 28 extending between the device's perimeter wall 20
and the mounting pad 12. As FIG. 1A illustrates,
conventional solder joint inner and outer fillets are
20   concave in shape.
        When a solder joint fails, two successive phases of
joint failure occur: crack initiation and crack propagation.
Crack initiation time is the time required for a crack to
first form in the solder joint. As FIG. 1B illustrates,
25   crack initiation generally begins on the inner fillet
surface 27. Crack propagation time, on the other hand, is
the time from crack initiation until the solder joint fails
electrically. The propagation phase consists of two stages:
propagation of the crack under the device end termination
30   22, as shown in FIG. 1C, and propagation in the outer fillet
28, as shown in FIG. 1D. Crack propagation in the outer
fillet typically occurs along a line that makes a 45 degree
angle with the horizontal extending from the bottom edge 21
of the device up to the outer surface 29 of the fillet. A
35   solder joint fails electrically when the crack propagates to
the outer fillet outer surface 29 or substantially thereto,
as illustrated in FIG. 1E, such that electrical continuity

is functionally broken between the termination 22 and its
associated mounting pad 12.

It has been demonstrated that solder joint life is
affected by three aspects of solder joint geometry: (1)
solder joint height h_o, defined as the vertical distance
between the device's bottom terminations and the vertically
adjacent mounting pads, as shown in FIG. 1A; (2) solder
joint inner fillet shape; and (3) solder joint outer fillet
shape. Crack initiation time tends to increase with
increased solder joint height h_o and with appropriately
designed inner fillet shape (i.e., with the inner fillet
angle α being greater than a certain minimum number of
degrees). Crack propagation time under the terminations
(i.e., stage I) tends to increase with increased solder
joint height. It also tends to increase with increased
distance between the inner fillet surface 27 and the bottom
edge 21 of the terminations; however, this distance is
determined by the geometry of the device's terminations and
is fixed for a given device. As for crack propagation time
in the outer fillet (i.e., stage II), this tends to increase
with appropriate outer fillet shape, particularly where the
shape requires that the crack propagate a longer distance.
Thus, overall solder joint life can be improved generally by
increasing the solder joint height and by appropriately
designing the shape of the inner and outer fillets.

One known method for increasing solder joint height is
to include "lifter pads" 30 beneath the non-solderable
bottom surface of the SMD, as shown in FIG. 2. According to
the prior art, these lifter pads are round in shape. When a
solder mass 32 deposited on a lifter pad melts during reflow
soldering, pressure within the molten solder mass provides
an upward force F_L which tends to lift the component, ideally
maintaining it at or above a minimum solder joint height h_o
until the solder mass returns to a solid state.

While this method does tend to increase solder joint
height, it makes no provision for the effect of the lifter
pad on solder joint geometry. As the component is lifted by

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the lifter pads, solder quantity at both the inner and outer
fillet areas is decreased as solder flows under the device
termination area to fill in the increased solder height,
thereby detrimentally altering solder joint geometry.

5   Similarly, surface tension and pressure forces within the
solder joint fillets detrimentally affect the shape and
lifting effectiveness of the molten solder masses atop the
lifter pads. Thus, using conventional lifter pads methods,
inner and outer solder joint fillets tend to change shape

10   and decrease in size, while lifter pad effectiveness in
increasing solder joint height is reduced due to the effect
of surface tension and pressure forces acting at the solder
joints. Thus, while overall solder joint height may be
increased, decreased overall crack propagation length and

15   unfavorable interior fillet angles α may result, such that
little or no overall improvement in crack initiation and
propagation time is achieved.

        Another approach for increasing solder joint height is
disclosed in "Prediction of Equilibrium Shapes and Pedestal

20   Heights of Solder Joints for Leadless Chip Components" (IEEE
Transactions on Components, Packaging, and Mfg. Tech.),
illustrated in FIG 3. Rather than using lifter pads, this
approach utilizes mounting pads whose outer edge 15 is
spaced closer to the SMD than is the case for conventional

25   mounting pads, so as to encourage the formation of convex
inner and outer fillets, rather than the typical concave
fillets. According to this approach, an amount of solder is
deposited on the mounting pads sufficient to "float" the
device on the solder to a desired solder joint height when

30   subsequently reflowed.

        This approach can be further illustrated by referring
to FIGS. 4 and 5. FIG. 4 shows a free body diagram of a
conventionally soldered (i.e., concave solder joint) SMD and
the forces acting thereon during and after reflow. A solder

35   joint height h_o is achieved when the net downward force on
the SMD (i.e., the weight W of the device, the ambient
pressure p_a, and the vertical components of the outer and

inner fillet surface tension forces, F_1 and F_2, respectively)
reaches equilibrium with the net upward force (i.e., the
buoyancy and contact force p_o provided by the solder joint).
Compare this with FIG. 5, which shows a free body diagram of

5   an SMD and the forces acting thereon during and after
reflow, utilizing convex solder joints. Note that the
vertical components of the surface tension forces F_1 and F_2
exert less downward force on the SMD than do the vertical
components of F_1 and F_2 in FIG. 4. In addition, the convex

10   shape in FIG. 5 guarantees that $p_o > p_a$ (i.e., a net upward
pressure force), while in FIG. 4 the concave shape suggests
that $p_a > p_o$ (i.e., a net downward pressure force),
particularly for devices having relatively wide solder
joints. Thus, by utilizing the convex joint geometry

15   illustrated in FIG. 5, a greater solder height h_o can be
achieved than can be realized by using the conventional
concave solder joint geometry.

        However, in practice both of the above prior art
methods are limited in their applicability by limits between

20   design of the mounting or lifter pads and the quantity of
solder which can be deposited thereon using the standard
solder paste deposition process (i.e., screen printing).
While other methods exist which can deposit additional
solder paste (e.g., dispensing), these are generally much

25   slower than screen printing and so are most practically
employed at additional cost only when needed.

        Furthermore, while both of these approaches may be
effective in achieving a desired solder joint height, they
unfortunately may have detrimental effects on solder joint

30   life. For example, the prior art lifter pad method produces
concave solder joints having a decreased distance between
the inner fillet surface and the outer fillet surface (i.e.,
decreased overall crack propagation length). Also, while
the prior art convex geometry method provides a solder joint

35   height which would increase stage II crack propagation time
somewhat, neither this method nor the prior art lifter pad
method addresses how to appropriately design the inner

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fillet geometry, nor how to optimize the mounting pad design
to maximize the outer fillet crack propagation distance.

It is desirable, therefore, to provide a method for
improving solder joint durability by achieving increased

5   solder joint height, optimized solder joint inner fillet
shape, and optimized solder joint outer fillet size and
shape.

According to the present invention, there is provided a

10   printed circuit board, comprising:
a printed circuit board substrate;
at least one surface mount device having a bottom
surface and a bottom edge about said surface, said device
having terminations on said bottom surface adjacent said

15   bottom edge;
at least two mounting pads for each of said
surface mount devices, said mounting pads being disposed on
a top surface of said substrate in matched relation with
said terminations of said surface mount device;

20   a solder joint connecting each of said
terminations with its respective mounting pad, said solder
joint having inner and outer fillets and consisting of a
predetermined amount of solder;
at least one lifter pad for each surface mount

25   device, each lifter pad being disposed on said top surface
of said substrate amid said mounting pads; and
a solder mass for each lifter pad, wherein each
solder mass is disposed between and in contact with its
respective lifter pad and said bottom surface of said

30   surface mount device, each solder mass consisting of a
predetermined amount of solder;
wherein said predetermined amounts of solder on
said mounting pads and each lifter pad in a molten state
provide a net buoyant force on said surface mount device

35   such that said device rises to a predetermined height above
said mounting pads, and wherein said solder in a solidified

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state maintains said device at substantially said
predetermined height above said mounting pads.

The embodiments of the present invention overcome the
disadvantages of the prior art by providing a surface mount
PCB having a substrate, at least one surface mount device,
at least two mounting pads per device, solder joints
connecting the terminations of the device to their
respective mounting pads, at least one rectangular lifter
pad on the substrate amid the mounting pads, and a solder
mass on each lifter pad in contact with the bottom surface
of the device. The inner and outer extensions of the
mounting pads, the size, number, and shape of the lifter
pads, and the amounts of solder deposited on the mounting
and lifter pads are optimized such that the solder joint has
preferably convex outer fillets, the device is maintained at
a predetermined height above the mounting pads, the inner
fillet angle is maintained above a predetermined minimum
angle, and the overall solder joint crack propagation length
is increased. An alternative embodiment also includes
plugged vias under the lifter pads and/or mounting pads,
with gas pockets trapped between the solder masses/solder
joints and the plugged vias. This trapped gas pocket
provides additional buoyant force upon the SMD during
reflow.

It is an advantage of the embodiments that the use of a
minimum inner fillet angle, in conjunction with an increased
solder joint height, promotes increased crack initiation
time.

It is a further advantage that the optimized outer
fillet shape, in conjunction with an increased solder joint
height, promotes increased crack propagation time.

Another advantage is that the rectangular-shaped lifter
pads provide a more effective means for providing buoyant
force upon the SMD than conventional round lifter pads.

Yet another advantage is that the rectangular lifter
pads and optimized solder joints, along with the plugged

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vias in the alternate embodiment, act together to float the
surface mount device to a desired solder joint height above
the PCB mounting pads without detrimentally affecting fillet
shape and overall crack propagation length.

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The invention will now be described further, by way of
example, with reference to the accompanying drawings, in
which:

FIGS. 1A-1E are longitudinal cross-section views of a
10   portion of a surface mount device soldered to a printed
circuit board, showing the successive phases of crack
initiation, crack propagation, and solder joint failure;

FIG. 2 is a longitudinal cross-section view of a
surface mount device soldered to a printed circuit board
15   according to the prior art, showing conventional solder
joints with lifter pads;

FIG. 3 shows a longitudinal cross-section view of a
solder joint according to the prior art having convex
fillets;

20   FIG. 4 shows a free body diagram of a solder joint
according to the prior art having concave fillets;

FIG. 5 shows a free body diagram of a solder joint
according to the prior art having convex fillets;

FIGS. 6A and 6B are longitudinal cross-section views of
25   a surface mount device soldered to a printed circuit board
according to the present invention, showing improved solder
fillet shapes in conjunction with either optimized lifter
pads or a plugged via/optimized lifter pad combination;

FIG. 6C is an enlarged cross-section view of a solder
30   joint according to the present invention;

FIG. 7 shows a representative plot of l_c versus l_0
within the range $0.5H < l_0 < 2H$; and

FIG. 8 shows an elevational view of a lifter pad and
solder mass according to the present invention.

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Referring now to the drawings, FIG. 6A shows a printed
circuit board with an SMD mounted thereon with optimized

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solder joints according to a first embodiment of the present
invention. This embodiment includes a PCB substrate 10
having a generally planar top surface, on which at least two
mounting pads 12 are disposed. These mounting pads 12 are
5   arranged on the top surface of the substrate 10 in matched
relation with terminations 22 of an SMD 14. Also on this
top surface are at least one lifter pad 30 for each SMD 14.
The lifter pads 30 for each SMD 14 are arranged amid the
corresponding mounting pads 12 for each respective SMD 14.
10 Thus, each PCB has a substrate 10 with one group of mounting
pads 12 and lifter pads 30 on its top surface for each
individual SMD 14 mounted thereon.
        The SMD 14 is a leadless surface mount device, such as
a leadless ceramic chip resistor (LCCR). The device 14 has
15 a generally rectangular top surface 16, a similarly shaped
bottom surface 18 oriented substantially parallel to the top
surface 16, and a perimeter wall 20 abutting the top and
bottom surfaces 16/18 and running around the entire
perimeter of the device 14. A bottom edge 21 is defined by
20 the intersection of the bottom surface 18 with the perimeter
wall 20. The SMD 14 also has terminations 22 on the bottom
surface 18 adjacent the device's bottom edge 21, arranged in
matched relation with the mounting pads 12 on the substrate
10. These terminations 22 may also extend up some or all of
25 the perimeter wall 20, and also onto some portion of the top
surface 16. The terminations 22 are electrically and
mechanically connected to their respective mounting pads 12
by means of solder joints 24, each joint 24 consisting of a
predetermined amount of solder.
30   Between each lifter pad 30 and the bottom surface 18 of
the SMD 14 is a solder mass 32, consisting of a
predetermined amount of solder. Each solder mass 32 is in
contact with both its respective lifter pad 30 and the
bottom surface 18 of the device 14.
35   The PCB according to the present invention is produced
by first providing a PCB substrate 10 having at least two
mounting pads 12 arranged on the top surface of the

substrate 10 in matched relation with the terminations 22 of
an SMD 14, and having at least one rectangular lifter pad 30
arranged on the surface amid the mounting pads 12. A
predetermined amount of solder is applied to the mounting
5   pads 12 and each lifter pad 30. This can be accomplished by
screen printing or other conventional deposition means,
usually according to a given overprinting strategy. After
this step the SMD 14 is placed onto the mounting pads 12
with the terminations 22 in matched relation thereto. Next,
10   the solder on the mounting pads 12 and lifter pads 30 is
heated, such as by placing the entire PCB in a solder reflow
oven. The heat will then melt the solder and the SMD 14
will float thereon above the mounting pads 12 due to the
buoyant force provided by the molten solder. Finally, the
15   molten solder is cooled, forming a solidified solder joint
24 atop each mounting pad 12 and a solidified solder mass 32
atop each lifter pad 30, such that the terminations 22 are
situated at the desired solder joint height h_o above the top
surface of the mounting pads 12, the interior angle α is
20   greater than a predetermined minimum angle, the outer fillet
28 is in contact with substantially the entire height of the
perimeter wall 20, and the solder joint outer fillet 28 is
preferably convex in shape. This creates a solder joint 24
which provides the desired solder joint height h_o while also
25   providing optimized solder joint structure which increases
crack initiation and crack propagation times.
        It should be noted that "optimized" solder joints, as
used herein, refers to joints 24 having interior angles α
greater than a predetermined minimum angle, outer fillets 28
30   contacting substantially the entire height of the device's
perimeter wall 20, a maximum stage II crack propagation
length l_c, and a solder volume V_M sufficient to provide the
desired solder joint height h_o, as illustrated in FIG. 6C.
Thus, it is often (but not always) the case that the outer
35   solder fillet 28 produced will be convex in shape. (It
should be noted that when the outer fillet 28 is convex, so
is the inner fillet 26, generally; likewise, when the outer

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fillet 28 is concave, so is the inner fillet 26.) However, there may be cases, such as when a very large solder joint height h_o is sought or a particular solder formulation is used, that the desired l_c crack propagation length and other

5   characteristics may be optimized while nonetheless producing concave outer fillets. The inner and outer extensions l_i/l_o and solder volume V_M which promote these solder joint characteristics are thus also referred to as being "optimized". Also, "optimized" lifter pads, as used herein,

10   refers to lifter pads 30 being rectangular (or, preferably, square) in shape, and having sufficient number, size, and solder mass volume V_{LP} so as to provide the buoyant force necessary to maintain the desired solder joint height h_o. Similarly, the solder volume V_{LP} calculated to promote this

15   is referred to as being "optimized". Furthermore, "optimized" crack initiation and propagation times refer to the maximization of these times, as produced by the combination of the foregoing optimized features.

The procedure for designing the first embodiment of the

20   present invention, as illustrated in FIGS. 6A and 6C, involves two general processes: (1) optimizing the solder joints 24 and mounting pads 12, and then (2) optimizing the solder masses 32 and lifter pads 30. Given as inputs into these two processes are: the dimensions and weight of the

25   SMD 14, the solder paste material properties (e.g., percent solder), the desired solder joint height h_o (e.g., 7 mils), the printing/overprinting strategy for solder deposition onto the mounting pads 12 and lifter pads 30 (e.g., 10 mil overprinting on three sides of each mounting pad), and the

30   number and dimensions of lifter pads 30 (e.g., six per SMD). Using these inputs, the desired outputs from the two optimization processes will be: the optimum mounting pad inner extension l_i (i.e., the horizontal distance from the termination inner edge 23 to the mounting pad inner edge 13)

35   which optimizes crack initiation time at the inner fillet 26, the optimum mounting pad outer extension l_o (i.e., the horizontal distance from the SMD bottom edge 21 to the

mounting pad outer edge 15) that optimizes crack propagation length l_c in the outer fillet 28, and the volume of solder paste on each mounting pad V_M and each lifter pad V_{LP}. Thus, given the provided inputs, the first process determines the geometric dimensions of the mounting pad 12 necessary to promote optimized crack initiation and propagation times, while the second process determines the solder mass volume necessary to float the device 14 (in conjunction with the buoyant force exerted by the solder joint 24) to the desired solder joint height h_o and maintain the desired solder joint geometry.

Each of these two optimizing processes will now be discussed in greater detail, using quantities from the following list of variables and constants:

h_o = desired solder joint height;

t = thickness of termination 22 on the bottom surface 18 of SMD 14;

h = height of solder joint at inner fillet 26 between top of mounting pad 12 and bottom surface 18;

H = height of solder on perimeter wall 20 measured from the bottom edge 21 (usually the same as the height of the SMD 14);

w = width of SMD 14 per solder joint 24;

W = weight of SMD 14 per pair of solder joints;

V_{calc} = calculated volume of solder on each mounting pad 12;

V_M = volume of solder on each mounting pad 12;

V_{LP} = volume of solder in each solder mass 32;

L = length of SMD 14;

l_c = crack propagation length in outer fillet 28, measured along line JK;

l_o = outward extension of mounting pad 12; (the horizontal distance from the bottom edge 21 to the mounting pad outer edge 15);

l_m = length of the bottom surface of termination 22;

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l_i = inner extension of mounting pad 12 (the horizontal distance from the termination inner edge 23 to the mounting pad inner edge 13);

G_p = gap between mounting pads 12 on respective opposite edges of the device 14;

G_c = gap between termination inner edges 23 on respective opposite edges of the device 14;

$G_{c,max}$ = maximum value of any G_c measurements for a given device 14;

$A_{T,max}$ = cross-sectional area of solder joint 24;

A_{CS} = cross-sectional area of solder mass circular segment 35, as shown in FIG. 8;

C_o = hypotenuse of triangle ABC in FIG. 6C;

C_i = hypotenuse of triangle A'B'C' in FIG. 6C;

C_{LP} = hypotenuse of triangle A''B''C'' in FIG. 8;

p_o = pressure in the solder joint 24;

p_a = atmospheric (reference) pressure;

σ = surface tension;

F = downward force acting on a single lifter pad 30;

F_o = upward force acting on SMD 14 due to the solder joint 24;

N = number of lifter pads 30 for every outer pad;

θ_o = angle between hypotenuse C_o and the outer fillet's free surface 29;

θ_i = angle between hypotenuse C_i and the inner fillet's free surface 27;

θ_{LP} = angle between hypotenuse C_{LP} and the solder mass outer surface 33;

θ_o' = angle between hypotenuse C_o and the vertical;

θ_i' = angle between hypotenuse C_i and the vertical;

θ_{LP}' = angle between hypotenuse C_{LP} and the vertical;

θ_c = angle between the solder mass free surface 33 and the bottom surface 18 of the SMD 14;

α = angle between the inner fillet surface 27 and the bottom surface 18 of the SMD 14;

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R = radius of curvature of outer fillet surface 27;

R_{LP} = radius of curvature of solder mass outer surface 33.

R_{chip} = the distance along the bottom surface 18 from the centerline of the solder mass 32 to the solder mass outer surface 33;

R_{pad} = the distance along the top of the lifter pad 30 from the centerline of the solder mass 32 to the solder mass outer surface 33;

r_{CG} = radial distance from centerline of solder mass 32 to centroid CG of solder mass circular segment 35;

J = point-of-origin located vertically halfway between bottom edge 21 and the top surface of mounting pad 12;

K = point of intersection between outer fillet surface 27, and a crack propagation line of length l_c starting at point J and making a 45 degree angle with the perimeter wall 20;

x_c, y_c = x- and y-coordinates of point M, the origin of a circle which describes arc AKB; and

C = temporary variable (defined below).

Optimizing the Solder Joints

The first step in optimizing the solder joints 24 is to design the inner fillet 26 such that the angle α between the fillet's free surface 27 and the bottom surface 18 of the device 14 is no smaller than about 30 degrees. This is accomplished by dimensioning the inner extension l_i such that

$$G_p = G_{c,max} + 3h, \qquad \text{--- (1)}$$
giving
$$l_i = (L - 2l_m - G_p)/2. \qquad \text{--- (2)}$$

Once the inner extension l_i has been determined, the remaining steps of the solder joint optimization process

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focus on determining the outer extension l_o, given the volume of solder V_M provided by the selected printing strategy, so as to form a preferably convex joint which achieves the desired solder joint height h_o while optimizing the crack
5   propagation length l_c as measured along line JK.

The second step is to select a starting value for the mounting pad outer extension l_o. A starting value is needed because finding the optimum l_o value is an iterative process.
10 A suggested range is $0.5H < l_o < 2H$, so a starting value of $l_o = 0.75H$ is recommended.

Third, the volume V_{calc} of the solder joint 24 is determined by calculating the amount of solder which can be
15 deposited given the selected l_o, the calculated l_i, the l_m associated with the given SMD, the width of the solder joint w, and the particular printing or overprinting strategy to be used (e.g., 10 mil overprinting using a 10 mil thickness of solder paste having 50% solder by weight). This
20 represents the amount of solder available during reflow to form the solder joint 24.

Using the anticipated geometric features of reflowed solder joint 24 as depicted in FIG. 6C, the volume V_M of solder in the solder joint 24 can be expressed as:
25      $$V_M = w(l_o/2)(H + h_o) + w(l_i/2)h + l_m h_o +$$
$$(w/4)\{C_o^2[\theta_o \csc^2\theta_o - \cot\theta_o] + C_i^2[\theta_i \csc^2\theta_i - \cot\theta_i]\} \quad \text{--- (3)}$$
        with
        $$A_{T,max} = V_M/w, \quad\quad\quad\quad \text{--- (4)}$$
        where
30      $$C_o = \sqrt{(l_o^2 + (H + h_o)^2)} \quad\quad\quad \text{--- (5)}$$
        and
        $$C_i = \sqrt{(l_i^2 + h^2)}. \quad\quad\quad \text{--- (6)}$$

In Eqn. 3, all the quantities are known except for V_M, θ_o, and θ_i. The angle θ_o can be determined (and the angle θ_i
35 eliminated) by setting V_M equal to V_{calc} proceeding as follows.

Fourth, a temporary variable C is defined by ignoring the portion of Eqn. 3 corresponding to the miniscule volume of the inner fillet circular segment 25 (i.e., the $C_i^2[\theta_i csc^2\theta_i - cot\theta_i]$ term), solving the equation in terms of the $[\theta_o csc^2\theta_o - cot\theta_o]$ binomial term, and setting the result equal to C:

$$C = [\theta_o csc^2\theta_o - cot\theta_o] = (4/C_o^2)[V_{calc}/w - (l_o/2)(H + h_o) - l_i h/2 - l_m h_o].$$ --- (7)

Fifth, the $csc^2\theta_o$ term of Eqn. 7 is converted into $(cot^2\theta_o + 1)$, yielding:

$$C = \theta_o csc^2\theta_o - cot\theta_o = \theta_o cot^2\theta_o + \theta_o - cot\theta_o.$$ --- (8)

The cotangent terms of Eqn. 8 are then series expanded to include only the first three terms in the series, giving:

$$C = \theta_o(1/\theta_o - \theta_o/3 - \theta_o^3/45)^2 + \theta_o - (1/\theta_o - \theta_o/3 - \theta_o^3/45).$$ --- (9)

Expanding the squared trinomial, ignoring the resulting higher-order terms, and combining like terms gives:

$$C = 2\theta_o/3 + 4\theta_o^3/45,$$ -- (10)

or further,

$$0 = \theta_o^3 + 15\theta_o/2 - 45C/4.$$ -- (11)

Ignoring the third-order term in Eqn. 11, a first-order approximation of θ_o can be stated as:

$$\theta_o = 3C/2,$$ -- (12)

wherein C can be determined using the latter part of Eqn. 7 above.

Once θ_o is determined, the sixth step is to calculate θ_o' using:

$$\theta_o' = tan^{-1}[l_o/(H + h_o)].$$ -- (13)

Seventh, a point $M(x_c, y_c)$ is defined as the center of a circle including arc AKB and having radius R; that is, point $M(x_c, y_c)$ is the center of curvature of the outer fillet free surface 29. x_c, y_c, and R are calculated using:

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$$R = C_o/(2\sin\theta_o), \quad\quad\quad\quad -- (14)$$
$$x_c = -l_o/2 + R\cos(\theta_o/2)\sin\theta_o', \quad\quad -- (15)$$

and

$$y_c = H/2 - R\cos(\theta_o/2)\cos\theta_o'. \quad\quad -- (16)$$

Eighth, the length l_c of the outer extension is determined using:

$$l_c = \text{abs val } \left[\frac{(x_c - y_c) \pm \sqrt{(2R^2 - (x_c + y_c)^2)}}{\sqrt{2}}\right] -- (17)$$

The ninth and final step of the solder joint optimization process is to repeat the second through eighth steps above in order to plot l_c versus l_o within the range suggested in the first step (i.e., $0.5H < l_o < 2H$). FIG. 7 shows a representative plot of l_c versus l_o for the suggested range. Then, the value of l_o is picked which corresponds to $l_{c,max}$, the maximum value of l_c. For example, in FIG. 7 the l_o value of $0.83H$ corresponds to the maximum value of l_c.

Once the optimum inner extension l_i, optimum outer extension l_o, and solder joint volume V_M are determined based on the given inputs, the lifter pads 30 and solder masses 32 can then be designed.

Optimizing the Lifter Pads

A critical aspect of lifter pad design is the ability to predict solder joint height h_o given (1) the geometry of the device 14 and the mounting pads 12, (2) the number, shape, and size of the lifter pads 30, and (3) the solder volume V_{LP} on each lifter pad 30. The geometry of the device 14 (i.e., $G_{c,max}$ and l_m) is determined by the particular device used in each case, while the mounting pad geometry (i.e., l_o and l_i) is calculated in the above solder joint optimization process.

The number and size of the lifter pads 30 is somewhat affected by the method of solder deposition. For instance, in the conventional screen printing solder deposition

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method, the best consistency (i.e., minimum percent
variation in solder volume) is usually obtained with stencil
apertures between 12 and 26 mils. Since it is desirable to
have many rather than fewer lifter pads (for improved

5   standard deviation of deposited solder volume), a stencil
aperture corresponding to the lower end of this range is
recommended. Also, smaller pads are more effective for
overprinting, and have less tendency to form solder balls
than do larger pads. (That is, in depositing as much solder

10   paste as possible without forming solder balls, a higher
solder volume-to-lifter pad area ratio is possible with
smaller pads than is with larger pads, generally.) Thus,
the size and number of lifter pads 30 will depend on the
available space underneath the component (i.e., G_p), the

15   stencil aperture, the minimum recommended spacing between
the stencil apertures, and the desired overprinting scheme.
It has been found that a generally recommended number of
lifter pads is three per solder joint, while the size R_{pad} of
the pads depends much more closely on the particular G_p,

20   stencil/deposition characteristics, and overprinting
strategy used.
     As for the shape of the lifter pads 30, conventionally
a circular shape is used. However, according to the present
invention it is recommended that rectangular-shaped lifter

25   pads be used. Rectangular, and preferably square, pads are
more effective than circular ones for overprinting (i.e.,
deposition of excess solder) since the corners of the pad
assist during solder "pullback" and wetting, but are not
covered by the bulk of the solder mass 32 after reflow. For

30   example, a square lifter pad 30 can be overprinted with
solder 10 mils beyond each of the square's four edges, thus
forming a square footprint of solder paste larger than and
covering the square lifter pad. Then, during reflow, the
solder paste will melt and the solder paste footprint will

35   shrink to a roughly circular footprint as surface tension
forces cause the solder mass 32 (and the SMD placed thereon)
to rise, transforming the heretofore flat, square solder

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deposition into a roughly columnar mass atop the lifter pad
30 whose diameter straddles and is essentially equivalent to
the width of the square pad.

As for the solder mass volume V_{LP}, an optimum solder
volume is desirable since inadequate solder volume will
result in low, perhaps concave fillets, while excessive
solder quantities will raise the fillet heights inordinately
and solder will be drawn under the component termination 22
from the bulk of the outer fillet 28, resulting in a shorter
crack propagation length in the outer fillet 28. The steps
given below provide the approximate design criteria to
estimate the solder volume V_{LP} required to achieve a desired
solder joint height h_o given the necessary geometric
information. (It should be noted that while the following
equations are for the case in which no metallizations
corresponding to each lifter pad exist on the underside of
the SMD, equations describing this case (e.g., for flip-
chips) may be found in the literature.)

The first step toward determining V_{LP} is to calculate
the relative pressure in the solder joint 24 using:

$$(p_o - p_a) = (2\sigma\sin\theta_o)/C_o. \qquad -- (18)$$

Second, the net upward force F_o acting on the SMD 14 due
to the solder joint 24 is calculated using:

$$F_o = w\{l_m[p_o - p_a - W/(2l_mw) - \sigma(\cos\theta_1 + \cos\theta_3]\} \quad --(19)$$

where

$$\theta_1 = \theta_o + \theta_o' \qquad -- (20)$$

and

$$\theta_3 = \theta_i + \theta_i'. \qquad -- (21)$$

Third, the downward force F acting on a single lifter
pad 30 is calculated using:

$$F = -F_o/N, \qquad -- (22)$$

where N is the number of lifter pads 30 for every
mounting pad 12.

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The fourth step is to select a starting value for θ_{LP}, the angle between hypotenuse C_{LP} and the solder mass outer surface 33, as shown in FIG. 8. A suggested range is $10° < \theta_{LP} < 40°$, so a starting value of $\theta_{LP} = 25°$ is recommended.

Fifth, R_{chip}, C_{LP}, and R_{LP} are calculated using:

$$R_{chip} = R_{pad} - h \cot(\theta_{LP} + \theta_c), \qquad\qquad -- (23)$$

$$C_{LP} = h\sqrt{(1 + \cot^2(\theta_{LP} + \theta_c))} = h/[\sin(\theta_{LP} + \theta_c)], -- (24)$$
and
$$R_{LP} = -C_{LP}/(2\sin\theta_{LP}) = -h/[2\sin\theta_{LP}\sin(\theta_{LP} + \theta_c)], -- (25)$$

where θ_c is an interface angle determined by the physical characteristics of the solder and the bottom surface 18 in contact with each other, as can be determined by one having skill in the art.

Sixth, the force on an individual lifter pad 30 is calculated using:

$$F' = \pi\sigma R_{chip}^2/R_o - 2\pi R_{chip}\sigma\sin(\theta_{LP} + \theta_c) \qquad\qquad -- (26)$$
where
$$R_o = -R_{LP}. \qquad\qquad -- (27)$$

Seventh, the fourth through sixth steps are iterated until a value for θ_{LP} is arrived at such that the value of F' equals the value of F calculated in the third step (Eqn. 22) above.

Eighth, A_{CS} and r_{CG} are calculated using:
$$A_{CS} = \tfrac{1}{2}(R_o^2)(2\theta_{LP} - \sin 2\theta_{LP}) \qquad\qquad -- (28)$$
and
$$r_{CG} = (R_{chip} + R_{pad})/2 + R_o[(4\sin3\theta_{LP})/(6\theta_{LP} - 3\sin2\theta_{LP}) - \cos\theta_{LP}]\sin(\theta_{LP} + \theta_c). \qquad\qquad -- (29)$$

The ninth and final step is to calculate the volume V_{LP} of each lifter pad solder mass 32 using:

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$$V_{LP} = \pi[hR_{chip}^2 + h(R_{pad} - R_{chip})(2R_{chip} + R_{pad})/3 +$$
$$2A_{cs}r_{CG}]. \qquad\qquad -- (30)$$

Once the solder joint optimization and lifter pad optimization processes are completed, the inner extension l_i, outer extension l_o, and solder volumes V_M/V_{LP} can be used with the given input information to construct the foregoing first embodiment.

A second embodiment of the present invention is shown in FIG. 6B. This embodiment is similar to the first, with the addition of plugged vias 34 and gas pockets 40 filled with gas 42 which assist the lifter pads 30 and solder masses 32 in providing additional upward force F_L against the SMD 14. The plugged via 34 consists of a via hole 36 formed through the substrate 10, with the hole 36 being at least partially filled with a plug material 38. Also, the lifter pads 30 have a hole 44 formed therethrough in this embodiment, the hole 44 thus defining an interior wall of the lifter pad 30. A pocket 40 is formed at the top of the plugged via 34, generally bounded on its top by the solder mass 32, on its sides by the solder mass 32 and/or interior wall of the lifter pad 30 and/or via hole 36, and on its bottom by the plug material 38. It is also possible to fill the via hole 36 entirely with plug material 38, so long as some amount of pocket 40 is formed; however, preferably the via 36 is only partially filled with plug material 38, so that a larger pocket 40 is formed and thereby permitting greater lift from the subsequent expansion of gas 42 trapped in the pocket 40.

The plugged vias 34 are designed to trap gas 42 during reflow, and provide gas expansion that tends to increase the solder mass height h beneficially while reducing the solder deposition quantity required for the given increase in solder joint height h_o. The gas 42 may consist of air or other ambient gas trapped in the pocket 40 when the solder

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mass 32 is deposited atop the lifter pads 30, as well as volatile gases released internally by the solder mass 32 during the high heat of reflow.

Various other modifications can be envisaged. For example, it is also possible to provide plugged vias 34 under the mounting pads 12 in addition to or instead of the plugged vias 34 underneath the lifter pads 30. Also, it is clear that the solder joints 24 and solder masses 32 may be composed of the same solder or solder paste.

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CLAIMS

1.   A printed circuit board, comprising:

a printed circuit board substrate (10);

at least one surface mount device (14) having a bottom surface (18) and a bottom edge (21) about said surface (18), said device (14) having terminations (22) on said bottom surface (18) adjacent said bottom edge (21);

at least two mounting pads (12) for each of said surface mount devices (14), said mounting pads (12) being disposed on a top surface of said substrate (10) in matched relation with said terminations (22) of said surface mount device (14);

a solder joint (24) connecting each of said terminations (22) with its respective mounting pad (12), said solder joint (24) having inner and outer fillets (26,28) and consisting of a predetermined amount of solder;

at least one lifter pad (30) for each surface mount device (14), each lifter pad (30) being disposed on said top surface of said substrate (10) amid said mounting pads (12); and

a solder mass (32) for each lifter pad (30), wherein each solder mass (32) is disposed between and in contact with its respective lifter pad (30) and said bottom surface (18) of said surface mount device (14) , each solder mass (32) consisting of a predetermined amount of solder;

wherein said predetermined amounts of solder (24,32) on said mounting pads (12) and each lifter pad (30) in a molten state provide a net buoyant force on said surface mount device (14) such that said device (14) rises to a predetermined height (h_0) above said mounting pads (12), and wherein said solder (24,32) in a solidified state maintains said device (14) at substantially said predetermined height (h_0) above said mounting pads (12).

2.   A printed circuit board as claimed in claim 1, wherein an inner extension (l_i) of each mounting pad (12) is

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of a predetermined length so as to promote an angle (α) between said bottom surface (18) of said surface mount device (14) and a free surface (27) of said inner fillet)26) to be at least as great as a predetermined minimum
5 angle.

        3.   A printed circuit board as claimed in claim 2, wherein said predetermined minimum angle is 30 degrees.

10   4.   A printed circuit board as claimed in claim 1, wherein said outer fillet (28) contacts substantially the entire height of a perimeter wall (20) of said surface mount device (14), thereby providing increased crack propagation length.
15

        5.   A printed circuit board as claimed in claim 1, wherein said outer fillet (28) of said solder joint (24) is convex in shape.

20   6.   A printed circuit board as claimed in claim 1, wherein an outer extension (l_o) of each mounting pad (12) is of a predetermined length so as to maximize crack propagation length in said outer fillet (28), said predetermined length being based on a preselected solder
25 deposition strategy.

        7.   A printed circuit board as claimed in claim 1, wherein each lifter pad (30) is rectangular in shape.

30   8.   A printed circuit board as claimed in claim 1, wherein said substrate (10) includes vias (34) formed therethrough and each lifter pad (30) includes a lifter pad hole (44) formed therethrough, each of said vias (34) being aligned with a respective lifter pad hole (44), said vias
35 (34) being partially plugged with a plug material (38), thereby defining a closed pocket (40) between said solder

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mass (32) and said plug material (38) where gas (42) may be
trapped and allowed to expand during reflow.

9.   A printed circuit board as claimed in claim 8,
wherein said plug material (38) is thermally conductive.

10.   A printed circuit board as claimed in claim 8,
wherein said substrate further includes additional vias
formed therethrough and said mounting pads include mounting
pad holes formed therethrough, said additional vias being
aligned with said mounting pad holes, said additional vias
being partially plugged with a plug material, thereby
defining a closed pocket between said solder joint and said
plug material where gas may be trapped and allowed to expand
during reflow.

FIG.1A   INITIAL SOLDER JOINT
          (AS MANUFACTURED)
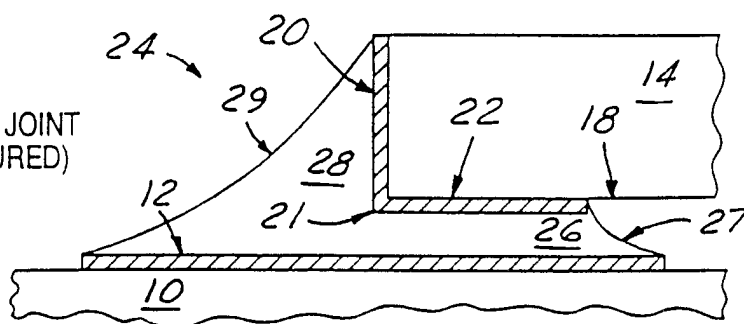
FIG.1B   CRACK INITIATION
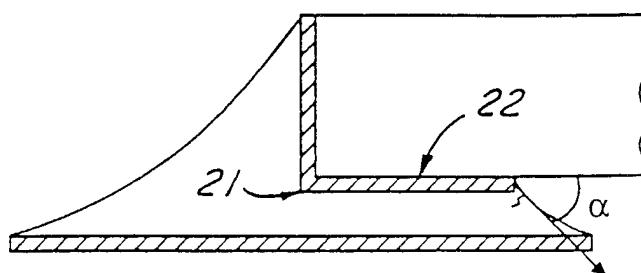
FIG.1C   CRACK PROPAGATION -
          PHASE I
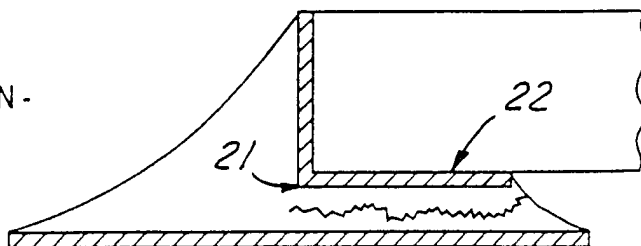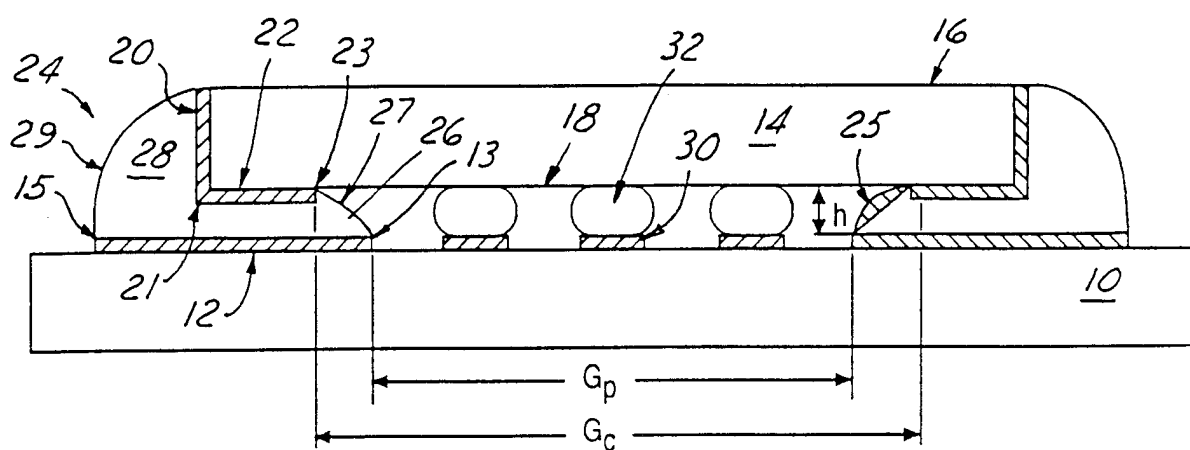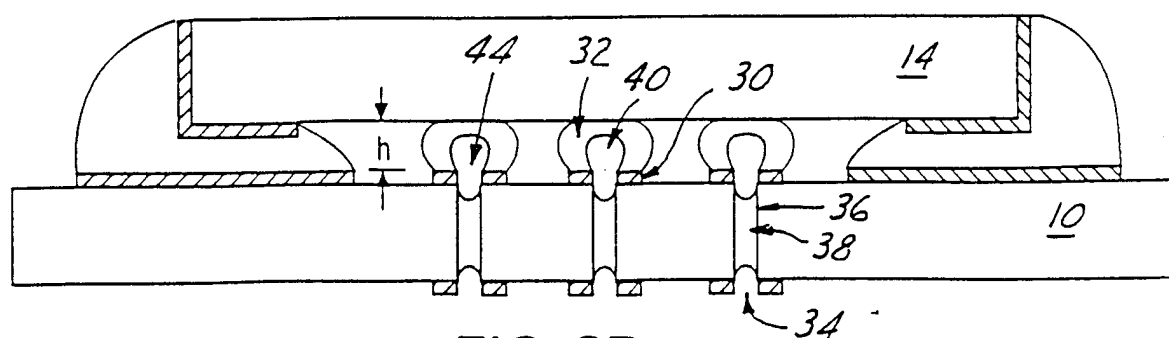
FIG.1D   CRACK PROPAGATION -
          PHASE II
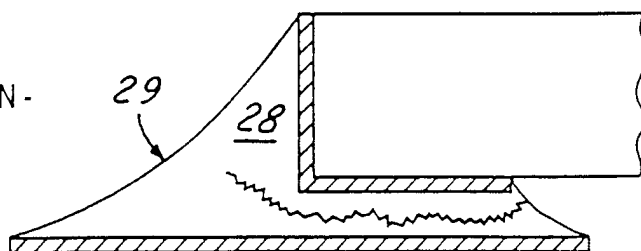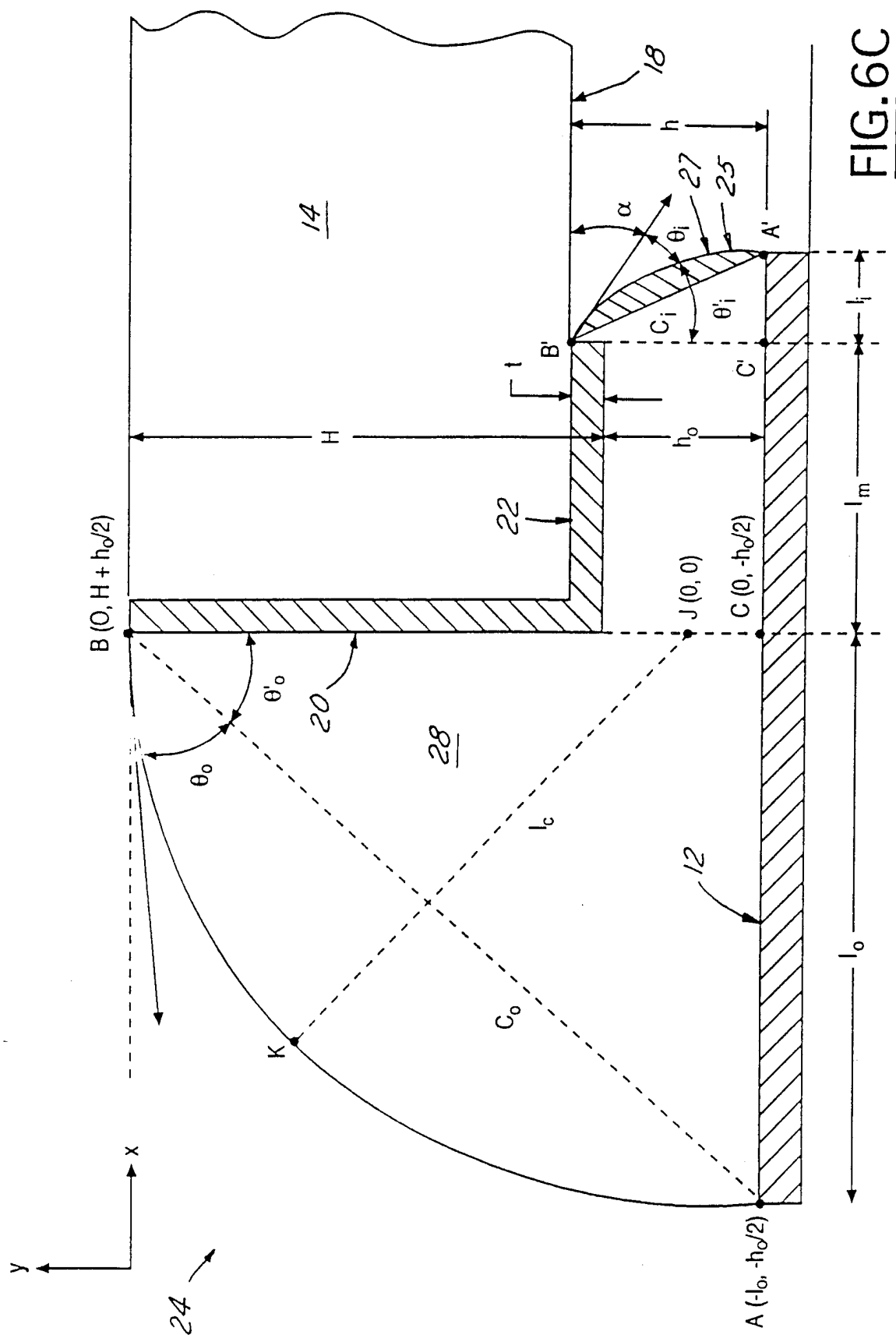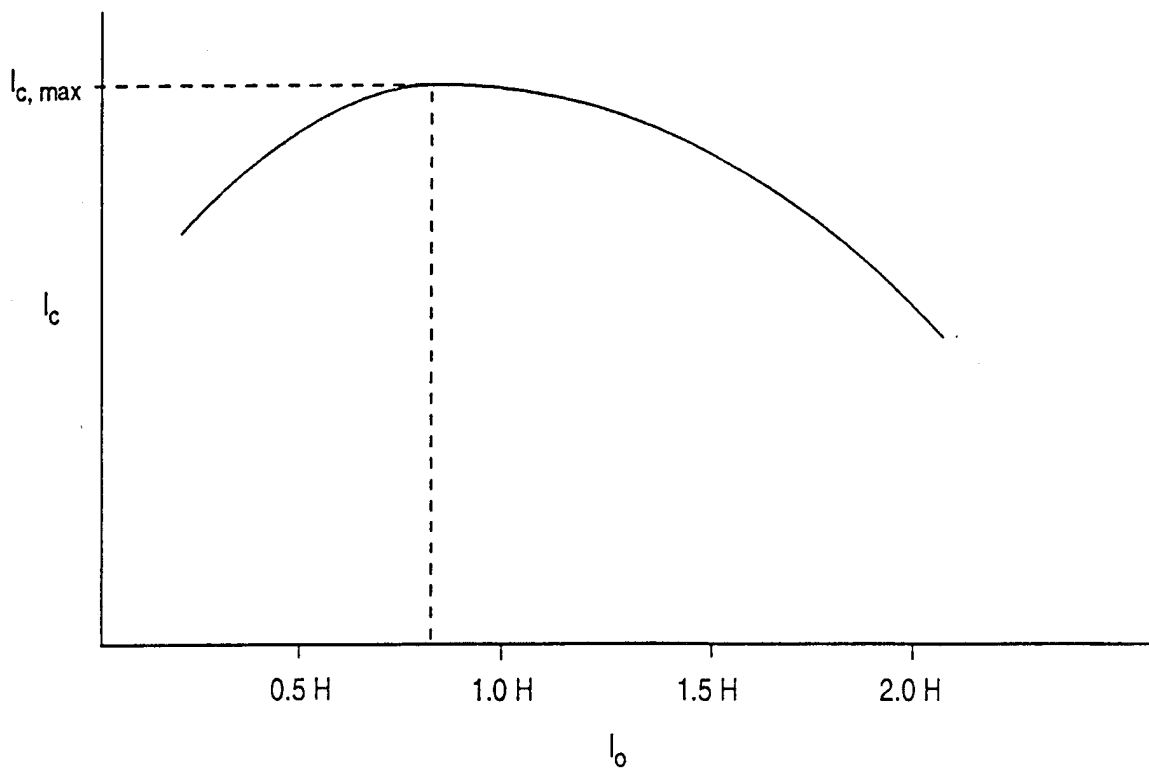
FIG.1E   SOLDER JOINT FAILURE

(PRIOR ART)

FIG.2

(PRIOR ART)

FIG.3

(PRIOR ART)

FIG.4
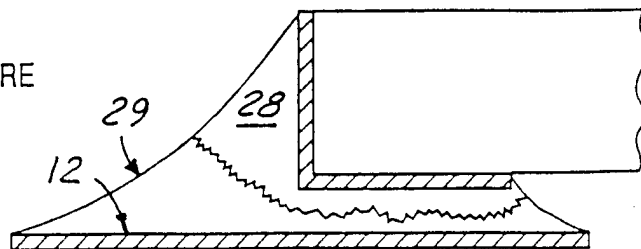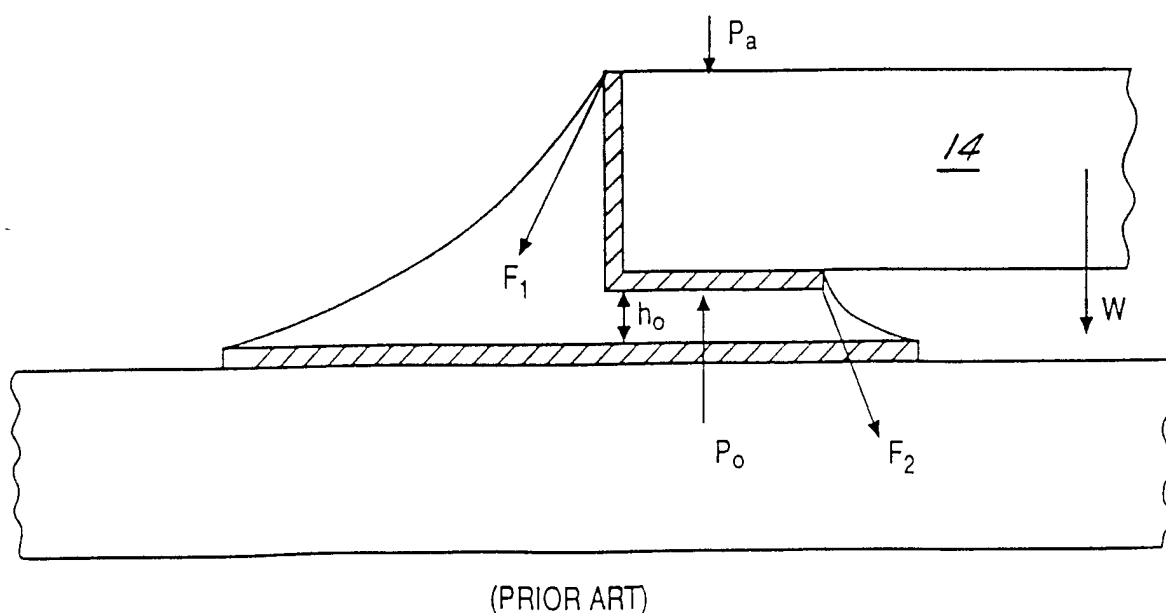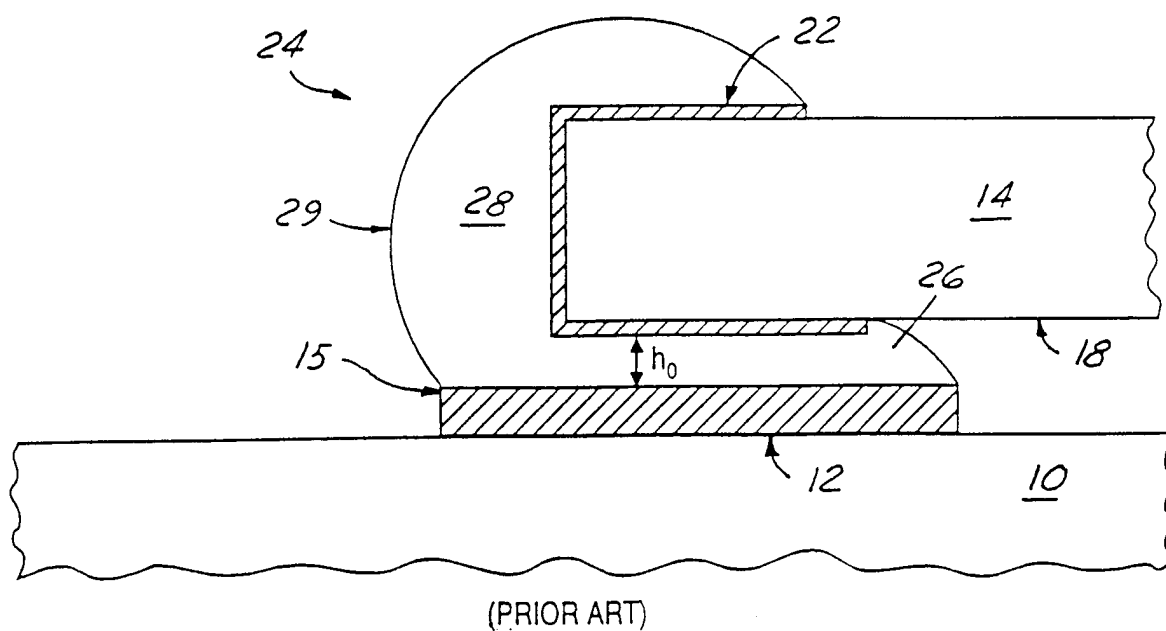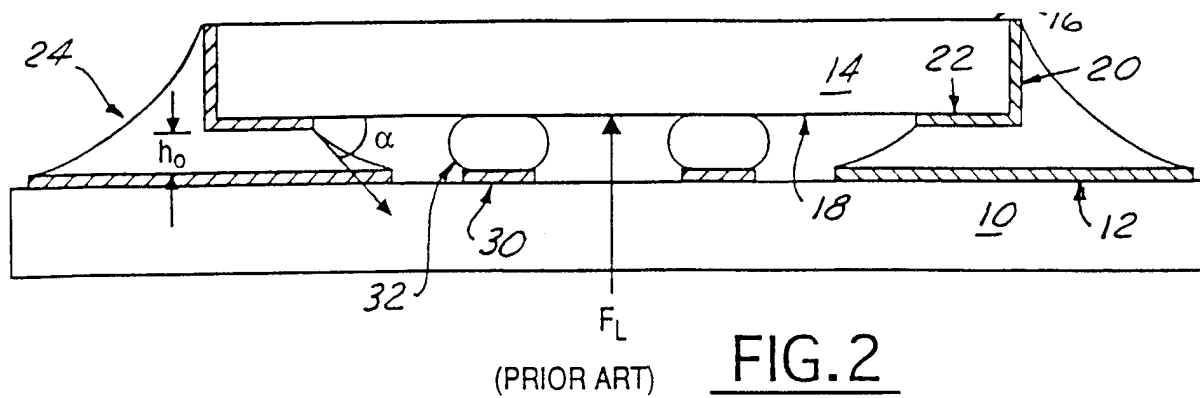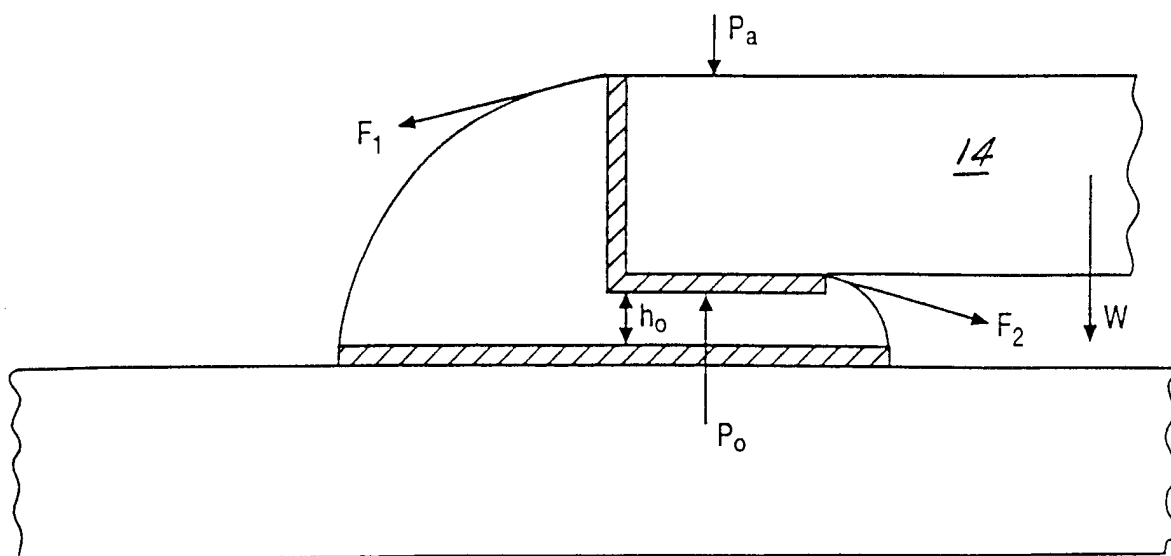
(PRIOR ART)

FIG.5

FIG.6A

FIG.6B

FIG.6C

FIG.7

FIG.8